Study Title: Expanded Pre-Drying Study and Comparison to POD

Background Information

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Key words: flash dry, oven dry, probability of detection

Abstract (less than 100 words):

The ETC II subtask included a comparison of the flash dry method to oven drying method for the purpose of predrying prior to application of penetrant. In the prior study[1] which used 40 Ni and 40 Ti cracks, ranging from approximately 40 to 120 mils, the drying temperatures were limited to the allowables for each method per AMS 2647 rev. B[2]. Brightness measurements were made using a spotmeter and digital images captured after processing using Level 4 postemulsifiable method (Magnaflux ZL-37). Significant statistical differences were not found for the sample size and crack sizes used in the study which compared flash and oven drying. To provide a broader consideration of the allowable temperature range and to enable a comparison to POD studies, a more comprehensive pre-drying study was performed and is described here.

Technical Summary

Purpose of Study:

Prior Work: The ETC II subtask on pre-drying studies (in preparation for FPI), utilized low cycle fatigue (lcf) cracks in Ni and Ti bars with crack sizes ranging from approximately 40 to 120 mils. Samples were placed in an acetone bath and ultrasonically agitated for 30 minutes, followed by an oven dry at 225°F (107°C) to ensure cracks were fully dry prior to the study. Samples were divided into two groups for either flash dry or oven dry, with a repeat study, and then exchanged to undergo the alternative drying method. This lead to all samples being dried with both methods, twice. Samples were placed in a water bath at room temperature (82°F (28°C)) to enable water to enter the cracks prior to drying. In the prior study temperatures from AMS 2647 rev. B were used as follows:

- Flash dry samples were placed in a flash dry tank at 150°F (66°C), the minimum temperature from AMS 2647 rev B

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[1] "Engineering Studies of Cleaning and Drying Processes in Preparation for Fluorescent Penetrant Inspection (FPI)," FAA Report to be published in Spring 2003.

[2] Society of Automotive Engineers (SAE) Aerospace Materials Specification AMS 2647 revision B, "Fluorescent Penetrant Inspection Aircraft and Engine Component Maintenance", published by SAE, Warrendale, PA, October 1999.

- Oven dry samples were placed in an oven at 225°F (107°C) for 30 minutes

All samples were cooled to 40°C prior to FPI. Ultrahigh sensitivity postemulsified method (Magnaflux ZL-37) was used with inspection parameters consistent with AMS 2647 rev. B. Brightness readings were made using a Spotmeter. Digital images of the cracks were recorded using Image Pro software. The following conclusions were arrived at in the prior work:

- Statistical analysis of brightness and UVA lengths did not reveal significant differences between the two drying methods at the temperatures used in the ETC study, i.e., flash drying at 150°F and oven drying at 225°F.
- Potential factors that were not considered in the ETC study are the effect of thermal mass, potential differences in penetrant sensitivity level, the effect of large cracks, and a range of drying temperatures.
- While significant differences were not found between the two methods, the importance of process monitoring and control for either method should be emphasized in specifications, standard practice documents, and training/guidance materials. Without careful adherence to the recommended practices, reductions in detectability can occur with either method.
- A comparison of the results of quantitative brightness measurements such as completed in the ETC program and the more traditional POD study is recommended.

Current Task: The purpose of this expanded study is to increase the temperature range considered for the two methods, to include other penetrants, and to compare the quantitative assessment made using the spotmeter to the results of a formal POD study.

Experimental Approach:

Through internal programs, Rolls Royce has generated an extensive sample set of over 200 cracks in forged Ni bars and which they have made available for this study. A subset of the cracks was selected to arrive at a sample set comprised of 81 samples, with a crack size distribution from 4 to 375 mils. The study was performed at the Delta Air Lines maintenance hanger as described below.

Specimens Used:

Rolls Royce has generated an extensive sample set of over 200 cracks in forged Ni bars such as the one shown Figure 1. The cracks were generated in three-point bending without the use of starter notches. Crack sizes range from 4 mils to 375mils with the majority of cracks from 10 to 100 mils. Additional crack characterization has been carried out at ISU in cooperation with Rolls. The characterization included optical measurements at 100 – 500X and digital recording. Based on the crack length measurements, 81 samples were selected for the drying studies which included twelve blanks. Appendix A provides a description of the sample selection process and information about the crack size distribution. All 81 samples were processed in batches for each parameter set.

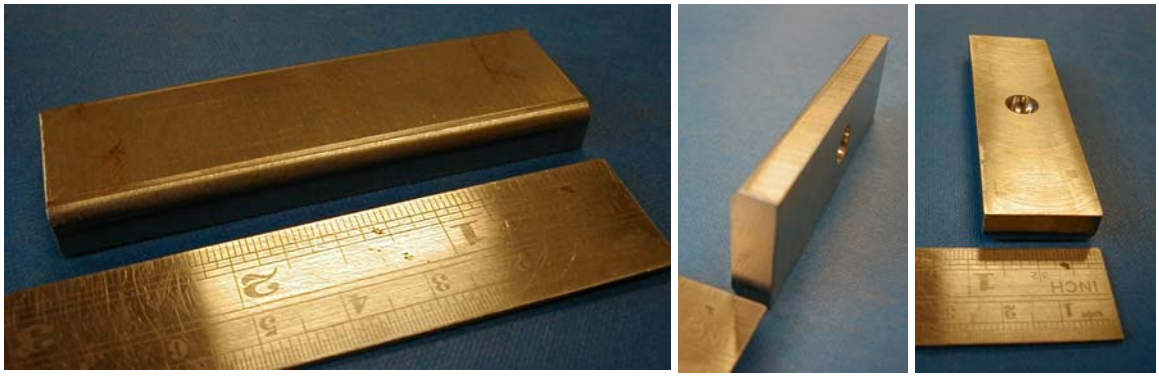


Figure 1. Sample used for the drying study with all dimensions shown (3" x 1" x ½") . Note the machined hole in the back of the sample which led to a localized increased stress leading to crack formation on the opposite face of the sample. The left image shows the sample face which contained the low cycle fatigue cracks.

FPI Chemistry:

Three penetrant systems[3] were used in the study:

- Level 4 ultrahigh postemulsifiable: Magnaflux ZL – 37
- Level 3 surfactant based water wash: Magnaflux ZL – 67
- Level 2 oil based water wash: Magnaflux ZL – 60D

Procedure:

Sample Preparation: Samples were viewed under blacklight prior to each run to ensure no bleed-out or contamination from prior studies. A 30 minute UT-acetone bath was used to clean samples between runs.

Sample set: An FPI run consisted of 81 samples run in three batches of 27. For a given run, up to six blanks were used with the number of blanks randomized from run to run using extra cracks from the extra crack set. Details of the crack selection and of processing parameters (drying method, penetrant type) were not known by the inspectors that participated in the POD study.

Trial Batch: A batch (set of 27 cracks) that covered the crack size range but skewed toward the smaller crack sizes was run to establish parameters and check the experimental process before proceeding to the full runs. The trial batch was ultrasonically agitated in acetone for 30 minutes followed by oven drying at the maximum temperature of 250°F to establish the drying time for use with all other runs. An emulsification time of 30 sec was used and a determination made of whether this should be changed for the formal runs. Spotmeter parameters were verified. The inspectors provided hit/miss determination and the data was recorded.

The cooling time was established as 30 minutes for the 250°F drying temperature. This time was used for all other drying studies regardless of temperature. An infrared pyrometer and

[3] The penetrants selected for this study are considered typical. Use of a particular product does not imply endorsement.

electronic thermocouple were used to measure the sample temperatures but inaccuracies were found. "Temperature strips" were then attached to samples to ensure actual oven temperatures were being reached. It was determined that the infrared pyrometer gave inaccuracies because of the reflective nature of the sample surface and its use was discontinued for the remainder of the study.

Wetting Method: To assure that the cracks had been exposed to water prior to drying, samples were placed in a basket inside of a plastic container and placed in the hot water (185°F) rinse tank for 10 minutes. The plastic container which held the sample was moved from the hot water and immediately flooded with a cold water bath for 5 minutes to bring the samples back down to ambient temperature prior to the drying step. This was an attempt to "trap" water inside the crack from the expansion/contraction cycle of the water baths. Foaming of the hot water bath was noted when the bath was agitated by the addition of the cold water as shown in the right of Figure 2. This was attributed to "blue soap" carry over from the cleaning steps for nickel parts.

Figure 2. Hot water rinse tank used for wetting the samples and for the flash dry method. The left image shows the samples in the basket which was placed inside of a plastic container and submerged in the hot water rinse tank. The right image shows the samples being cooled back to ambient temperature using a cold water rinse. This same tank was used for the flash dry method and was operated at 185°F through out the study.

Pre-Drying Methods:

The following drying parameters were used:

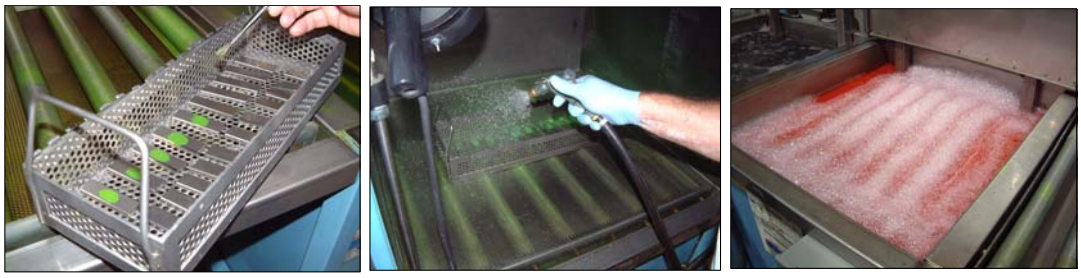
- Flash drying at 185°F. Samples were immersed in the hot water bath for 30 minutes as shown in Figure 2.
- Oven drying at 225°F (AMS T) and 250°F (RR T) for 30 minutes using controlled furnaces shown in Figure 3.

Figure 3. Oven dry facilities made available for the study. The far oven of this three oven furnace was utilized for all oven dry steps. Each of the three ovens is independently controlled.

FPI Parameters::

All samples were processed by a single individual for all runs. Parameters used for each of the steps are listed below with selected images provided in Figure 4.

1. Apply penetrant solution and allow to dwell for 20 minutes. A brush was used to apply the penetrant as shown in Figure 4 (a).
2. Spray wash for 60 seconds for the level 4 penetrant.
   Spray wash for 120 sec for the level 3 penetrant.
   Spray wash for 60 sec for the level 2 penetrant.
3. Immerse in emulsifier for 120 seconds for level 4.
4. Spray wash specimens for 60 seconds for level 4
5. Dry specimens at 150°F for 10 minutes
6. Apply dry developer using a drag through technique and a clean, dry container. Dwell 10 minutes prior to inspection. This developer application method was used for all three penetrant types.



(a) (b) (c)

(d) (e)

Figure 4 (a) Penetrant being applied over the lcf crack with a brush. (b) Penetrant spray rinse. (c) Emulsifier station used for level 4 penetrant. (d) Oven used for drying samples prior to application of developer. (e) Developer applied to sample by dragging through dry developer powder.

Inspectors: Two inspectors were used for the study. A data recorder was used with each inspector. The choice of inspector to see the samples first was randomized.

Evaluation:

Samples were evaluated using the spotmeter technique[4]. Brightness was recorded for the indication, including background. Total dwell time was recorded. Images were captured using ImagePro software and the samples made available for evaluation by the two inspectors. Equipment settings were as follows in Table 1:

Table 1. Equipment settings used for brightness measurements and digital data recording

Equipment	Settings
Photo Research PR-880 photometer / UVP XX-BLB 17" fluorescent UVA source	½" aperture, auto gain / 4960-5020 μWatts/cm^2
Moritex video microscope / Olympus high-intensity UVA Source with saline light guide, ImagePro image capture software	40X magnification, maximum sensitivity / 5,000 μWatts/cm^2

[4] "Spotmeter Spot Size versus Measured Brightness", Rick Lopez, available at http://www.cnde.iastate.edu/faa-casr/fpi

Samples were inspected using typical POD study protocols[5]. Hit/miss data was recorded for each sample. POD curves were generated for each of the two inspectors. Solvent wipe and magnification were not used as part of the evaluation process. The inspectors did not wear filtered glasses. Note that the results generated in the study are for comparison of parameter sets only and should not be considered valid POD data for use in life management calculations. While the cracks are typical of low cycle fatigue cracks that you might find in engine materials, all cracks were located in the same location on the samples.

Data Analysis: Statistical analysis of the data was performed at ISU using the software package, S-Plus. POD curves for inspectors were generated by Ward Rummel as described in Appendix B and using software developed by Rummel.

Results

The study matrix for the program is shown in Table 2 with a schedule of the studies as performed at the airline facility in Table 3. Level 4, oven dry at 225°F was used as a baseline parameter set and therefore four runs were made with this parameter combination at various points in the study. This parameter combination was also used in the prior ETC studies and allows comparison between the two studies. Note that to complete a run (three batches of 27 samples) and prepare (clean and dry) the samples for the next run was approximately a five hour process which lead to several long work days.

Table 2. Study matrix providing details of the oven dry and flash dry temperatures versus the penetrant levels. The number of runs per combination is indicated.

Drying Method	Oven Dry		Flash Dry
Temperature	250°F	225°F	185°F
Level 4	1	1 partial run at 60 sec emulsification 3 full runs at 120 sec emulsification	2
Level 3		1	1
Level 2		1	1

Table 3. Schedule and description of the eleven runs made at the airline facility.

[5] US Department of Defense Military Handbook: Nondestructive Evaluation System Reliability Assessment MIL-HDBK-1823, April 1999

Monday	Tuesday	Wednesday	Thursday	Friday
Equipment setup Sample preparation	Run 2 – OD – 225 – Level 4 – 120 sec emulsification	Run 4 – OD – 250 – Level 4	Run 7 – FD – 185 – Level 3	Run 10 – OD – 225 – Level 2
Run 1 – OD – 225 – Level 4 – 60 sec emulsification using partial set of samples	Run 3 – FD – 185 – Level 4	Run 5 – OD – 225 – Level 4	Run 8 – OD – 225 – Level 3	Run 11 – FD – 150 – Level 2
		Run 6 –FD – 185 – Level 4	Run 9 – OD 225 – Level 4	

Data was tabulated for each of the runs and used for statistical analysis. Figure 5 shows the log of brightness results for runs two through eleven plotted as a function of crack length. Significant differences were found between the machined and shot peened samples as shown by the different linear fits in Figure 5. Note that the results indicate increasing brightness with penetrant level with level 4 being greater than level 3 which is greater than level 2. Figure 6 and Figure 7 provides data for each of the surface treatments. The correlation coefficient ($R^{2)}$ values are also reported for each of the runs. Note that the values are higher for the machined samples than for the shot peened samples, an indication of the higher variability with the shot peened samples. The results also show considerable scatter for the largest cracks. The points at the far right of the graph are for two cracks of sizes 0.37" (sample A15A) and 0.375" (sample A40). A contributor to the variability may be the brightness measurement process. As discussed in reference 4, the brightness measurements are dependent on the spot size selection for the photometer. The spot size remained constant throughout this study and for crack sizes greater than approximately 0.120", only a portion of the crack would be in the measurement area of the instrument. Figure 8 provides an expanded view of the results for Level 4 penetrant for those cracks which were within the spotmeter focal area. Note there are some smaller crack size samples that also show variability. Review of the images for these samples indicates bleedout from the crack which contributed to the variability.

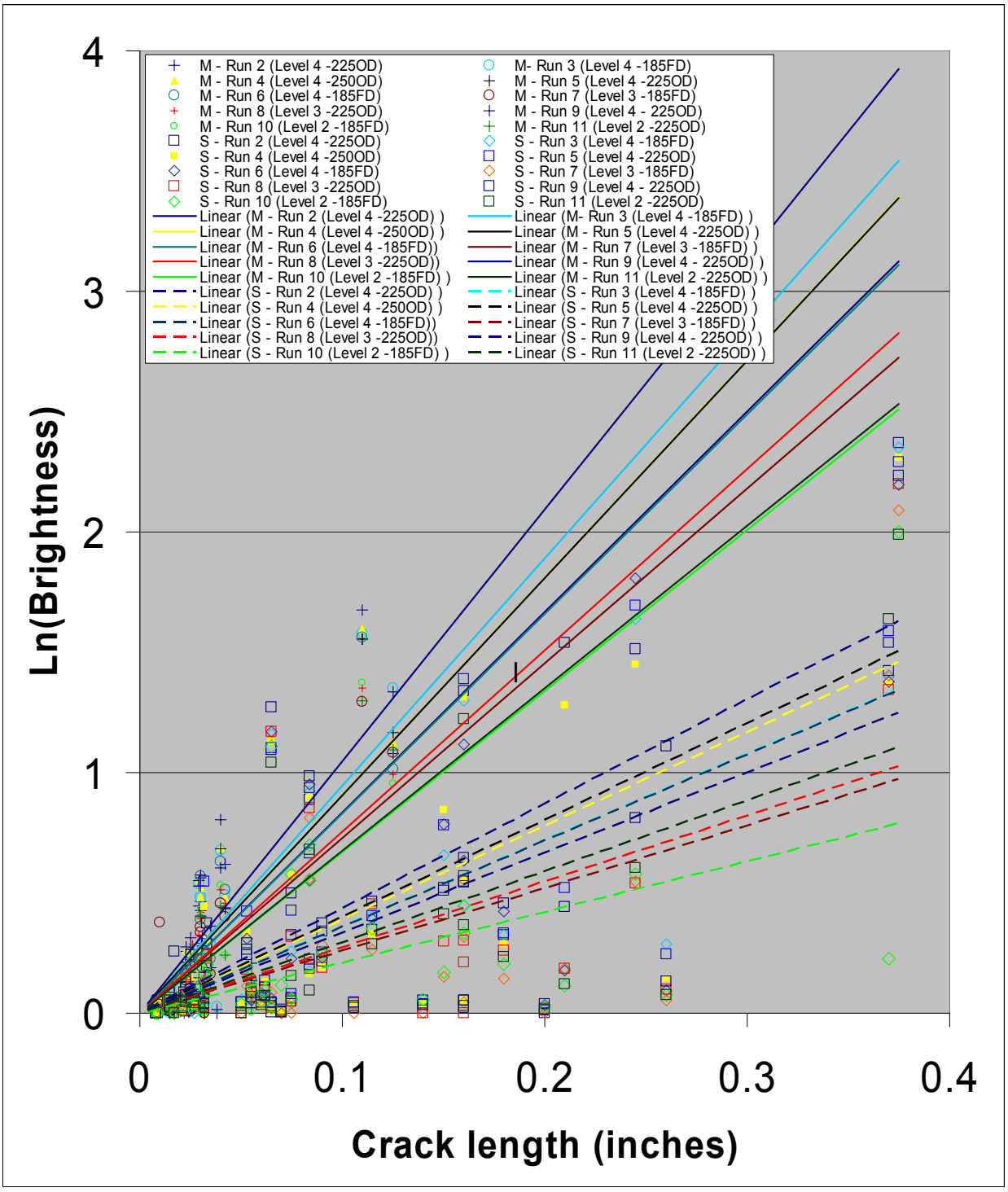


Figure 5. Brightness versus crack length, plotted for runs 2 through 11. Linear fit is also plotted for each of the datasets. Note that the linear fit for several of the datasets overlap (run 4 and 5 machined, runs 2 and 6 machined, runs 10 and 11 machined, and runs 3 and 6 shot peened).

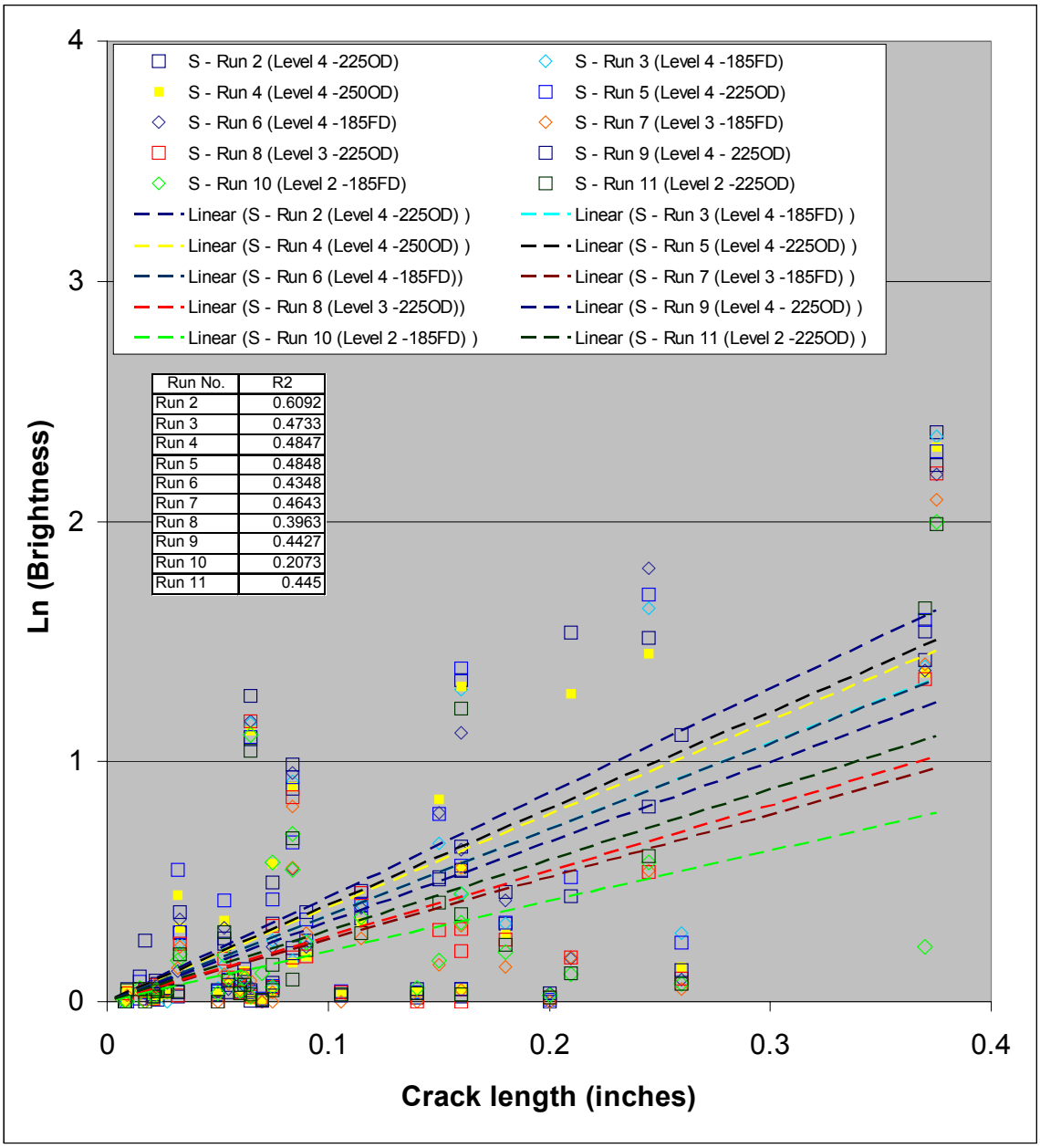


Figure 6. Brightness versus crack length results for only shot peened samples. Note inset of correlation coefficient (R^2) values for each of the runs included with the graph. As in Figure 5, several of the linear fit lines overlap.

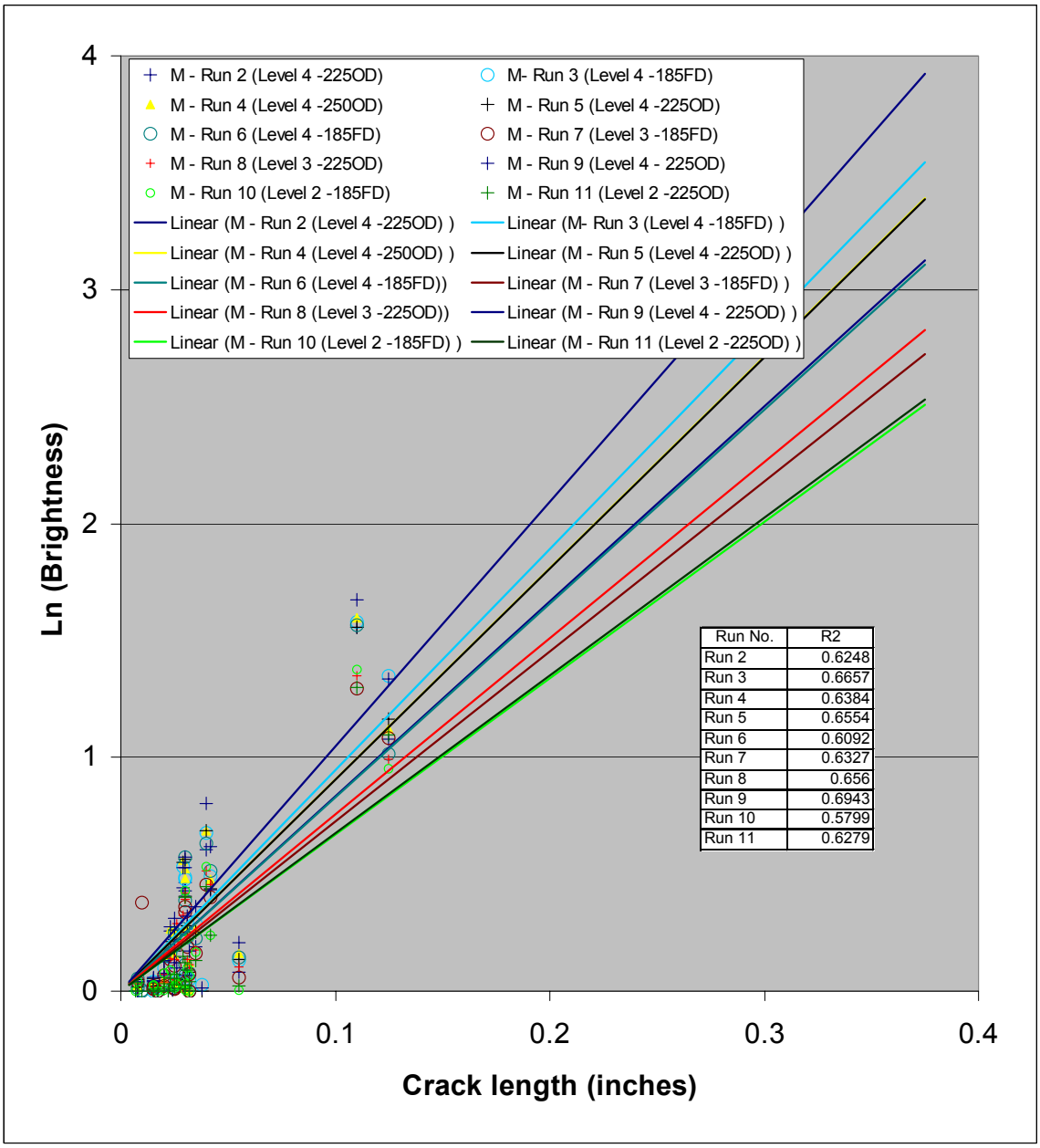


Figure 7. Brightness versus crack length results for only machined samples. Note inset of correlation coefficient (R^2) values for each of the runs included with the graph. As in Figure 5, several of the linear fit lines overlap.

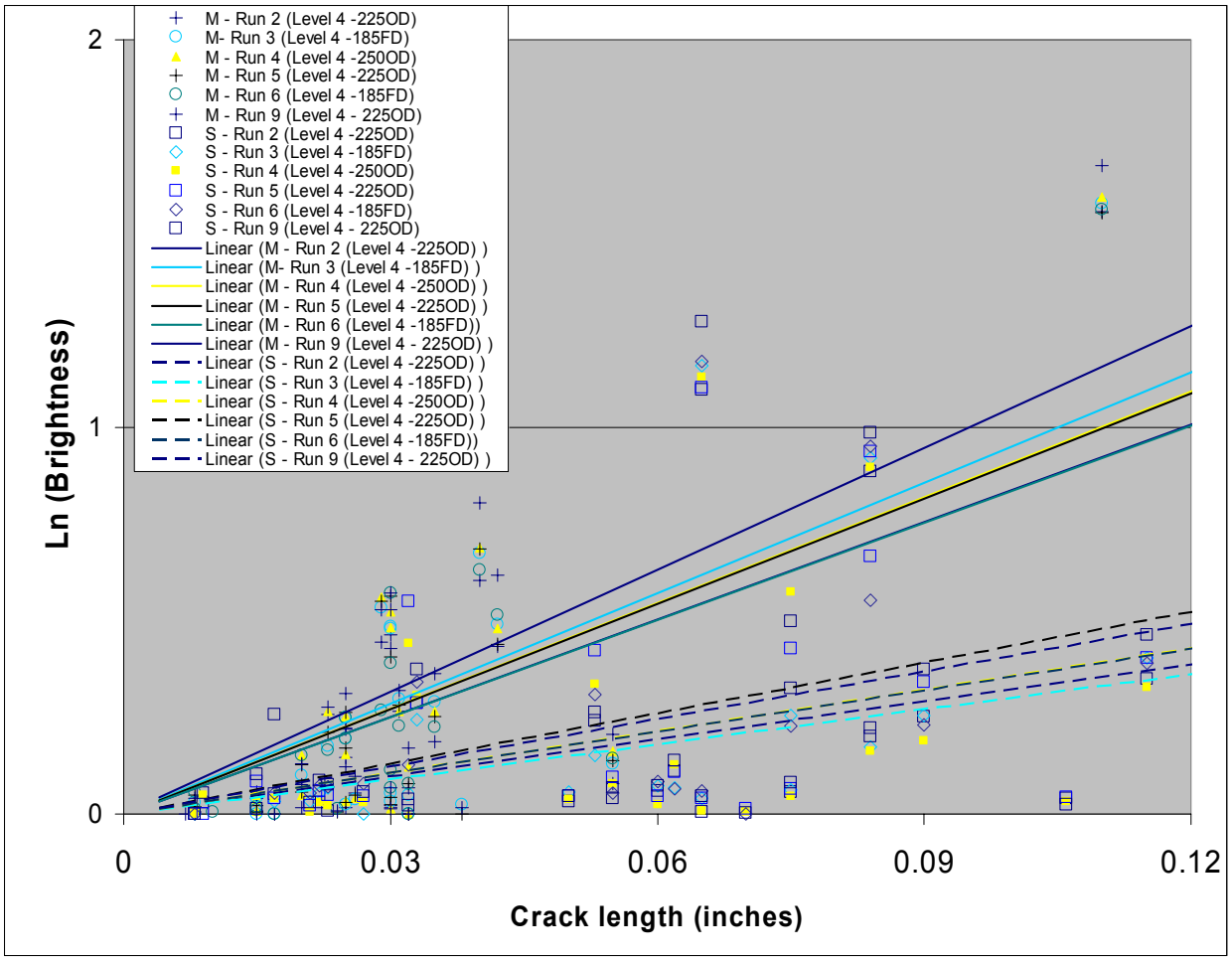


Figure 8. Brightness versus crack length plotted for Level 4 application to those samples that contain cracks that did not exceed the spotmeter measurement area. Note the expanded scale which enables a closer review of the variability of the measurements for a given sample. Several of the linear fit lines overlap including runs 4 and 5 machined, runs 2 and 6 machined, and runs 4 and 6 shot peened.

Recording of usable UVA images was quite difficult for this sample set using the available light source, filters and camera, particularly for samples that were shot peened. Four samples were selected as examples for reporting here. Figure 9 shows the brightness profiles for the four samples. The crack size and surface finishes are shown in the insert table. Note the decreases in brightness for the Level 3 and Level 2 penetrants compared to the Level 4. Two of the samples, A21 and A40, were selected because they show some of the largest variability for a given sample. A40 was the largest crack used in this study and UVA images are provided for runs 2 through 11 in Figure 10. The brightness variability results from the crack being larger than the photometer measurement area as discussed above and in reference 4. Figure 11 through Figure 13 provides UVA images of the other three samples. Figure 11 and Figure 12 show results for two typical samples, A11A and B3 respectively. Sample A11A was a machined surface while sample B3 had a shot peened surface. There is some evidence of the machining lines on the UVA images. Figure 13 provides results for sample A21. As noted above and as evidenced in the graph included with the UVA images, this sample showed some variability in its brightness response. The sample did contain multiple cracks or branching cracks as shown by the UVA images.

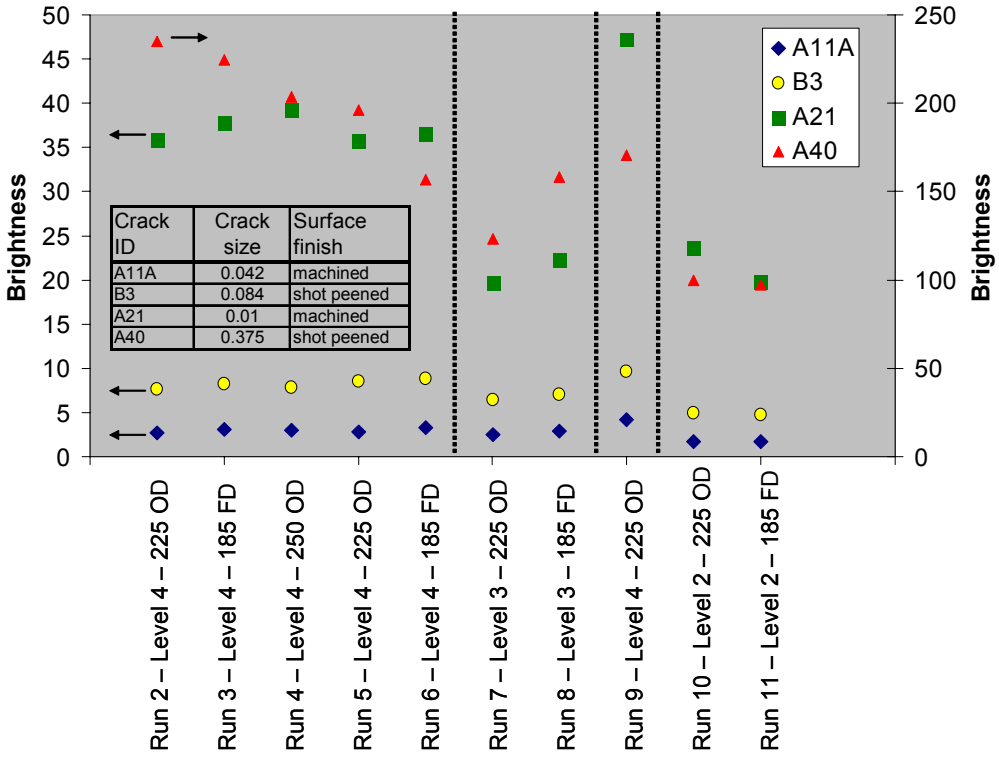


Figure 9. Brightness results for four typical samples. Note that two scales were used as indicated by the arrows. The inset table provides crack size and surface finish.

While the UVA results for these four samples are representative of those samples for which images were captured, there were a number of samples for which image capture was not feasible. While the sensitivity of the photometer was sufficient to measure brightness for the samples, the equipment being used for image capture did not have sufficient capability to capture images. This was particularly a problem with those samples that had been shot peened. It was recommended that consideration be given to different camera and/or filters to enhance image capture in future studies.

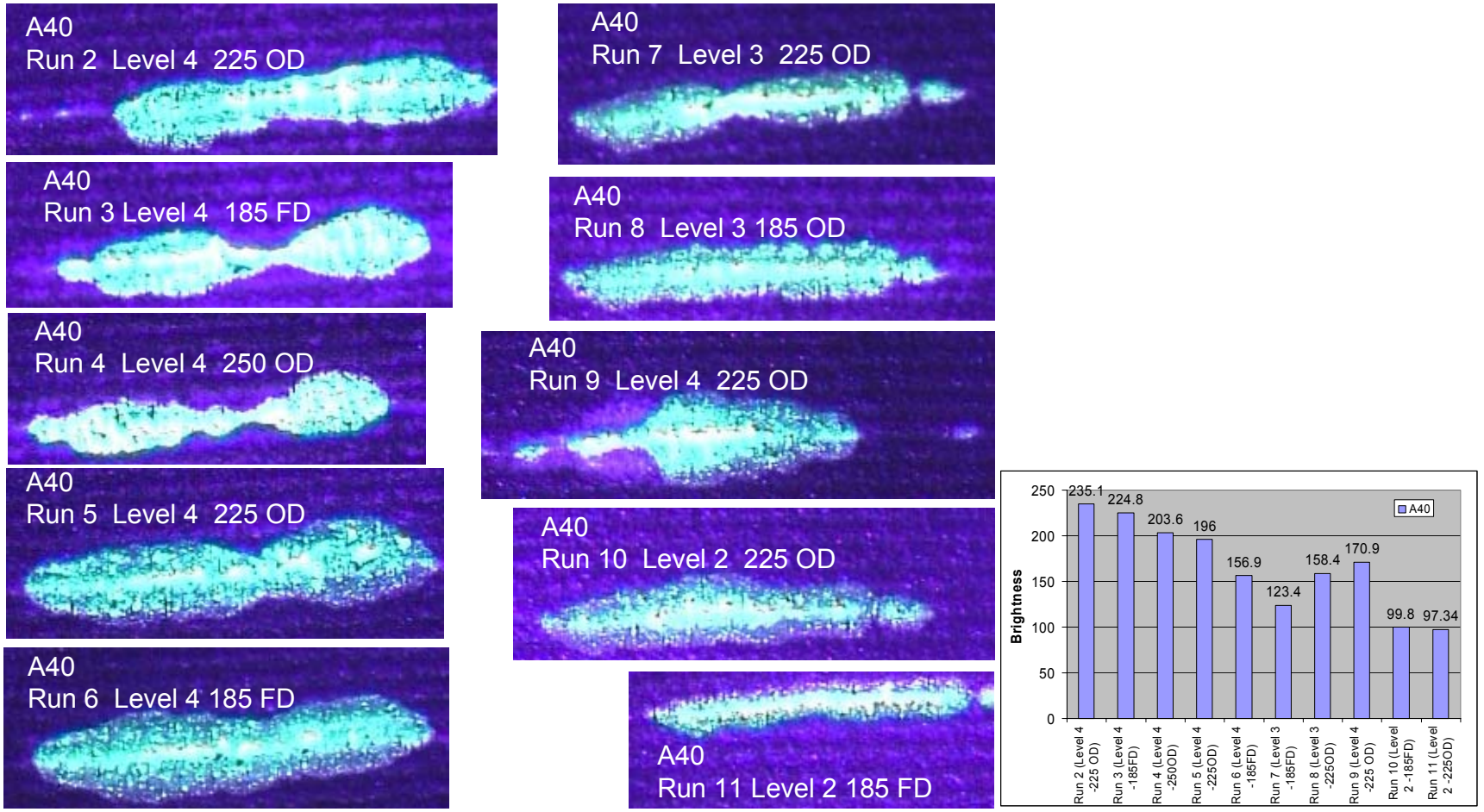


Figure 10. UVA images for sample A40, a 0.375" crack in a shot peened sample. Images are shown for each of the runs. Penetrant level and drying method are included with the image. This sample contained the largest crack used in the study. Note that the crack exceeds the measurement area of the photometer contributing to variability in the brightness readings.

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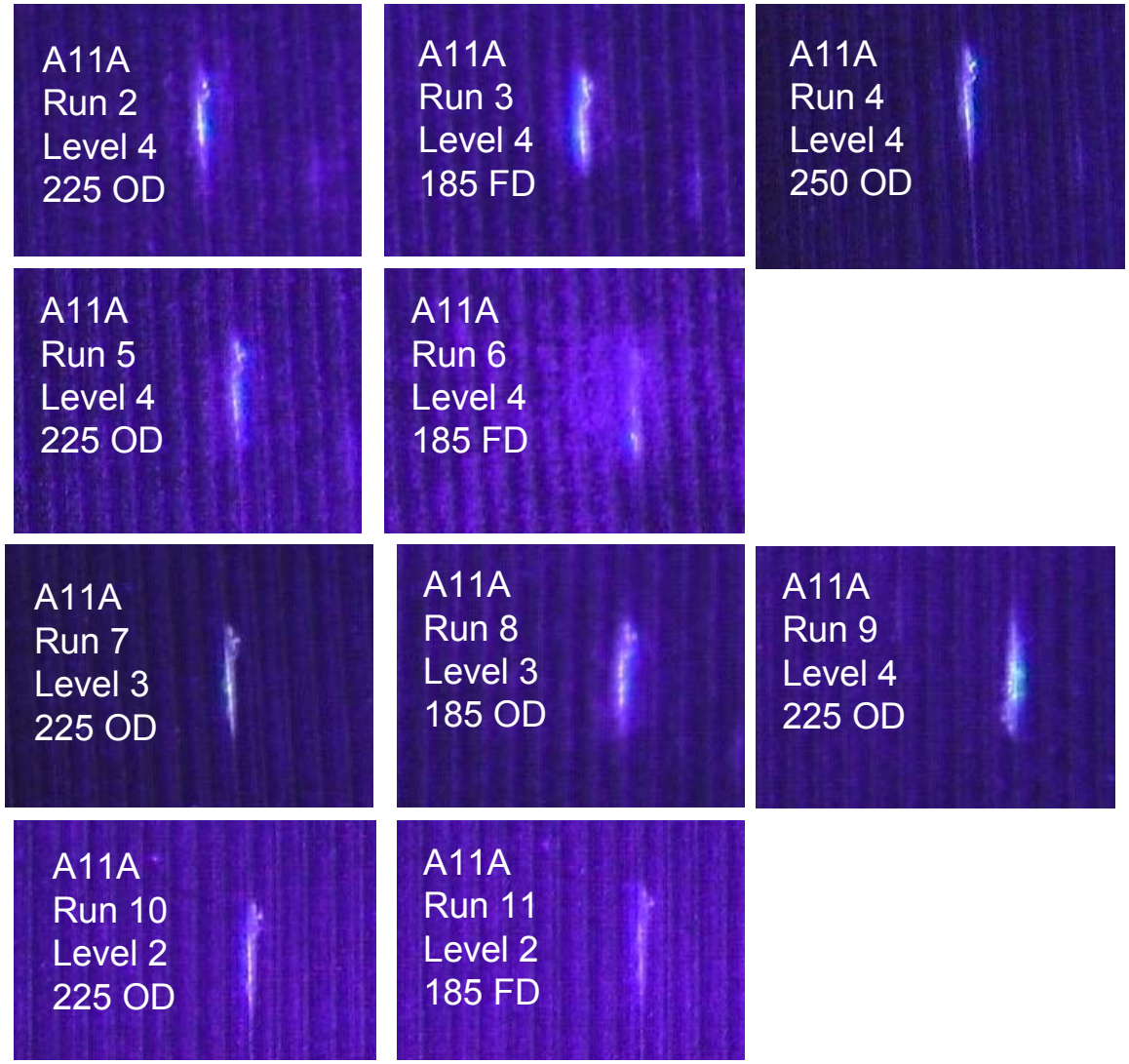

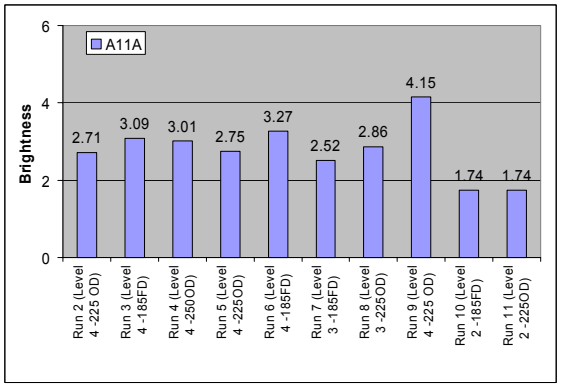

Figure 11. UVA images for sample A11A, a 0.42" crack in a machined sample. Images are shown for each of the runs. Penetrant level and drying method are included with the image.

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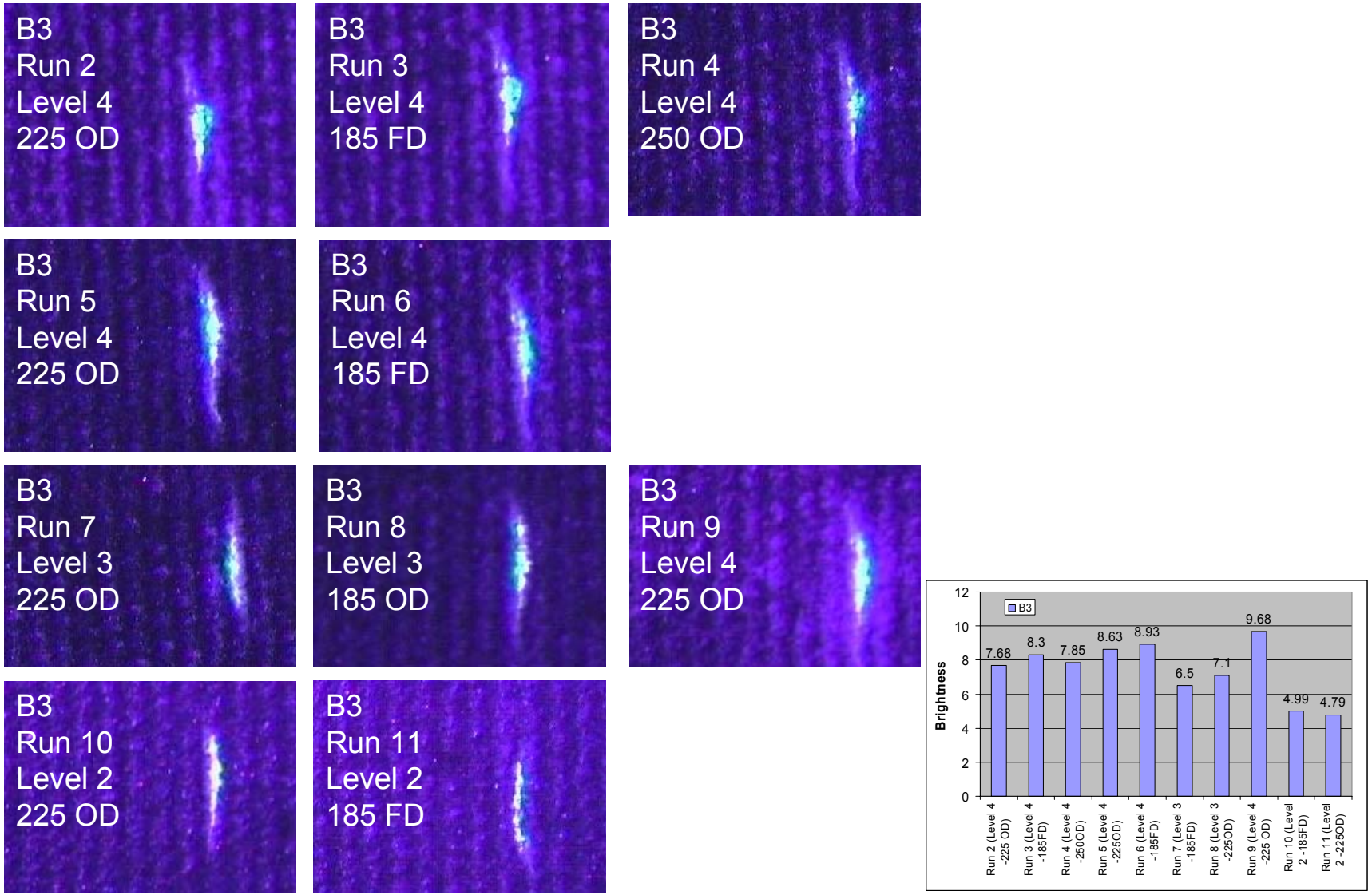

Figure 12. UVA images for sample B3, a 0.084" crack in a shot peened sample. Images are shown for each of the runs. Penetrant level and drying method are included with the image.

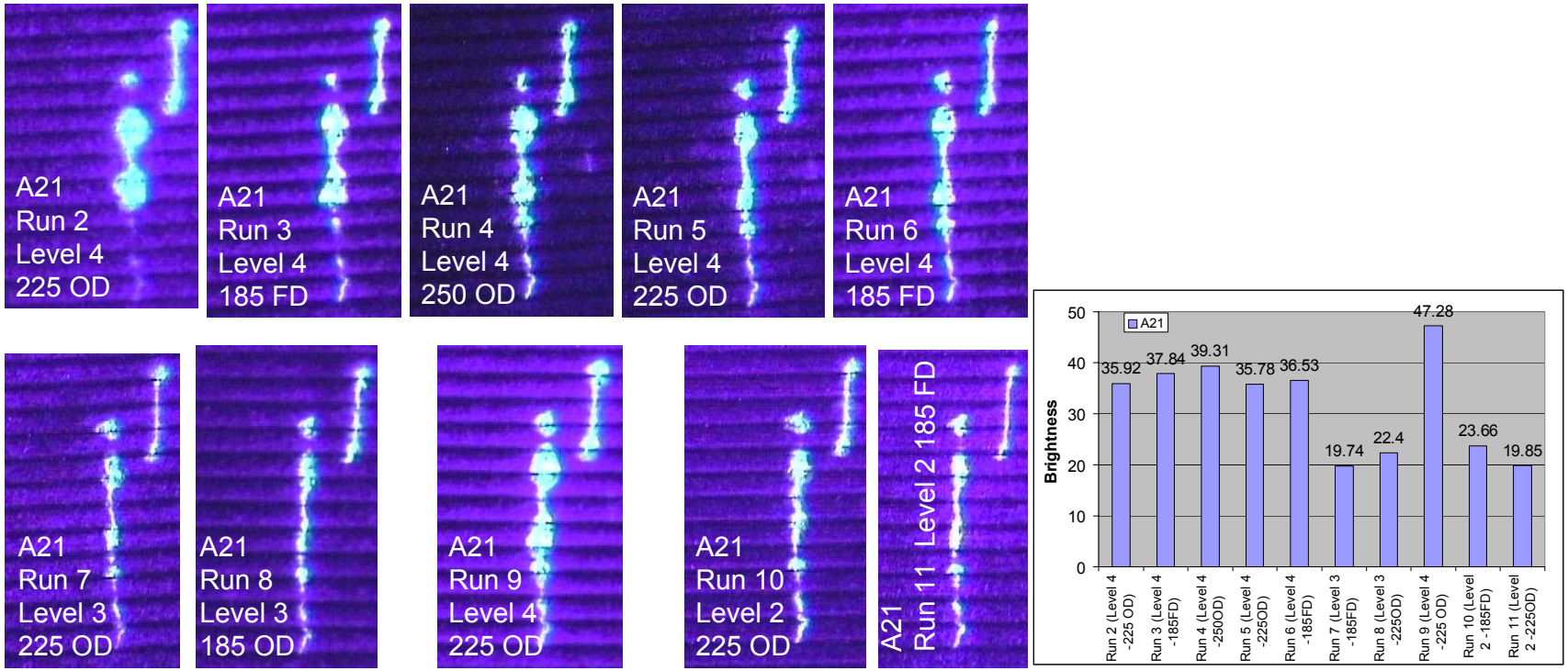

Figure 13. UVA images for sample A21, a 0.010" multi-crack in a machined sample. Images are shown for each of the runs. Penetrant level and drying method are included with the image.

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Statistical analysis tools were used to evaluate the various factors present with this sample set. The sample set allowed evaluation of surface finish (machined vs. shot peening), penetrant level, and drying method. The log of brightness is plotted versus optical crack size for each of the surface finish conditions and for each penetrant level as shown in Figure 14 . The statistical analysis used to generate the regression lines shown here has taken into account potential saturation effects for those UVA indication lengths that extend outside the focal area of the spotmeter (treated as censored data). Figure 14 groups all drying methods together for a given penetrant type/surface finish combination. Note the differences in slope for the machined and shot peened samples, with the machined surface finish brighter for a given crack length than the shot peened samples. Differences were also found between penetrant levels with Level 4 being the brightest for a given crack size. The plots in Figure 15 show the results as separated for the flash dry and oven dry methods. Significant differences were not found between the two drying methods using regression techniques.

A second analysis was completed to compare level 4 penetrant with level 2 and 3 penetrants (earlier analyses suggested that level 4 was better than levels 2 and 3 and that levels 2 and 3 were similar). The analysis compared the average for the level 4 penetrant brightness to the average for levels 2 and 3 penetrants to allow a paired comparison as shown in Figure 16. The plots show one point for each specimen, showing the mean under the two penetrant groups and the "ideal" line. Points falling below the line have averages that are larger for penetrant level 4, i.e., indicates higher brightness for penetrant level 4 than levels 2 and 3. For the larger averages, penetrant level 4 always dominates levels 2 and 3. For the smaller signal strengths (lower brightness), there is not much difference. Doing the usual paired t-test (details in the plot notes) provides strong evidence that penetrant level 4 has more brightness than penetrant levels 2 and 3 (at least for the specimens that have higher levels of brightness).

In addition to analysis of the brightness results, the inspector (POD) results were also analyzed. The misses (find =0) and finds (find = 1) were plotted for the two surface conditions in Figure 17. POD curves were generated by Meeker as shown in Figure 18. Curves were generated for the penetrant types using both an “ahat vs. a” type analysis and using the hit/miss data as recorded for the two inspectors. Note that for both analysis methods, the machined samples had better detectability when compared to the shot peened samples. Level 4 also showed better detectability than Level 2/3.

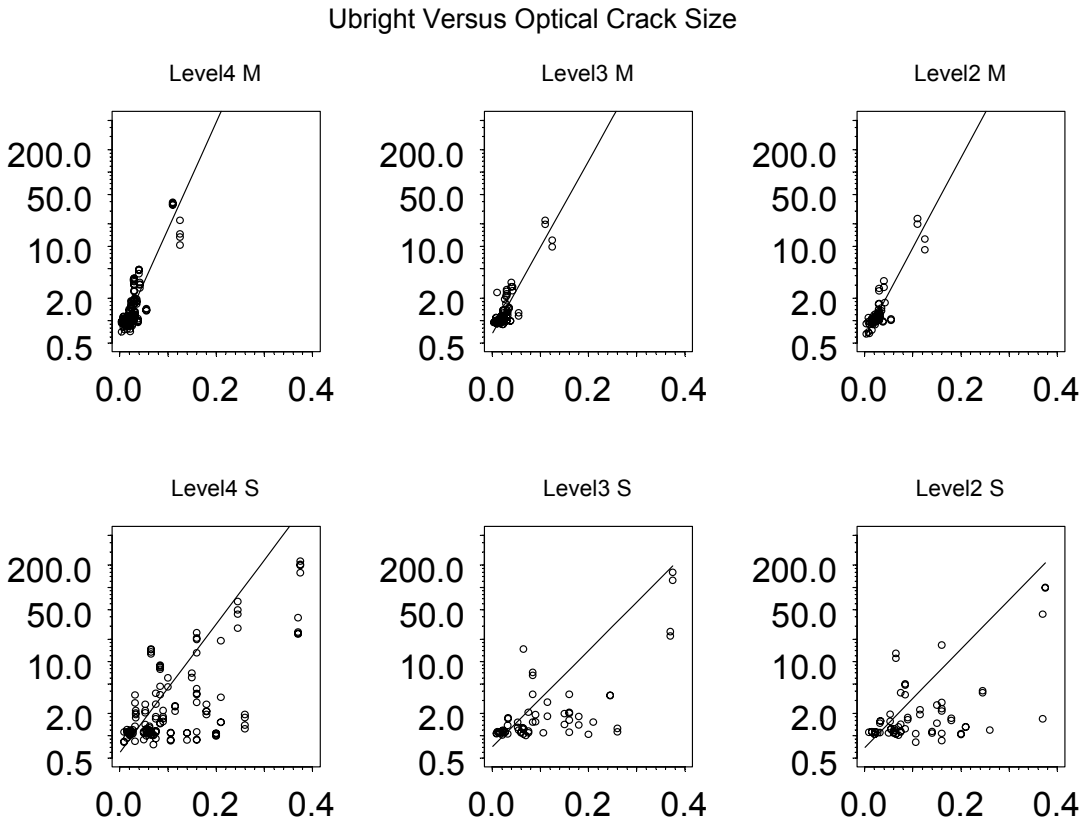


Figure 14. Regression data for brightness versus optical crack lengths.

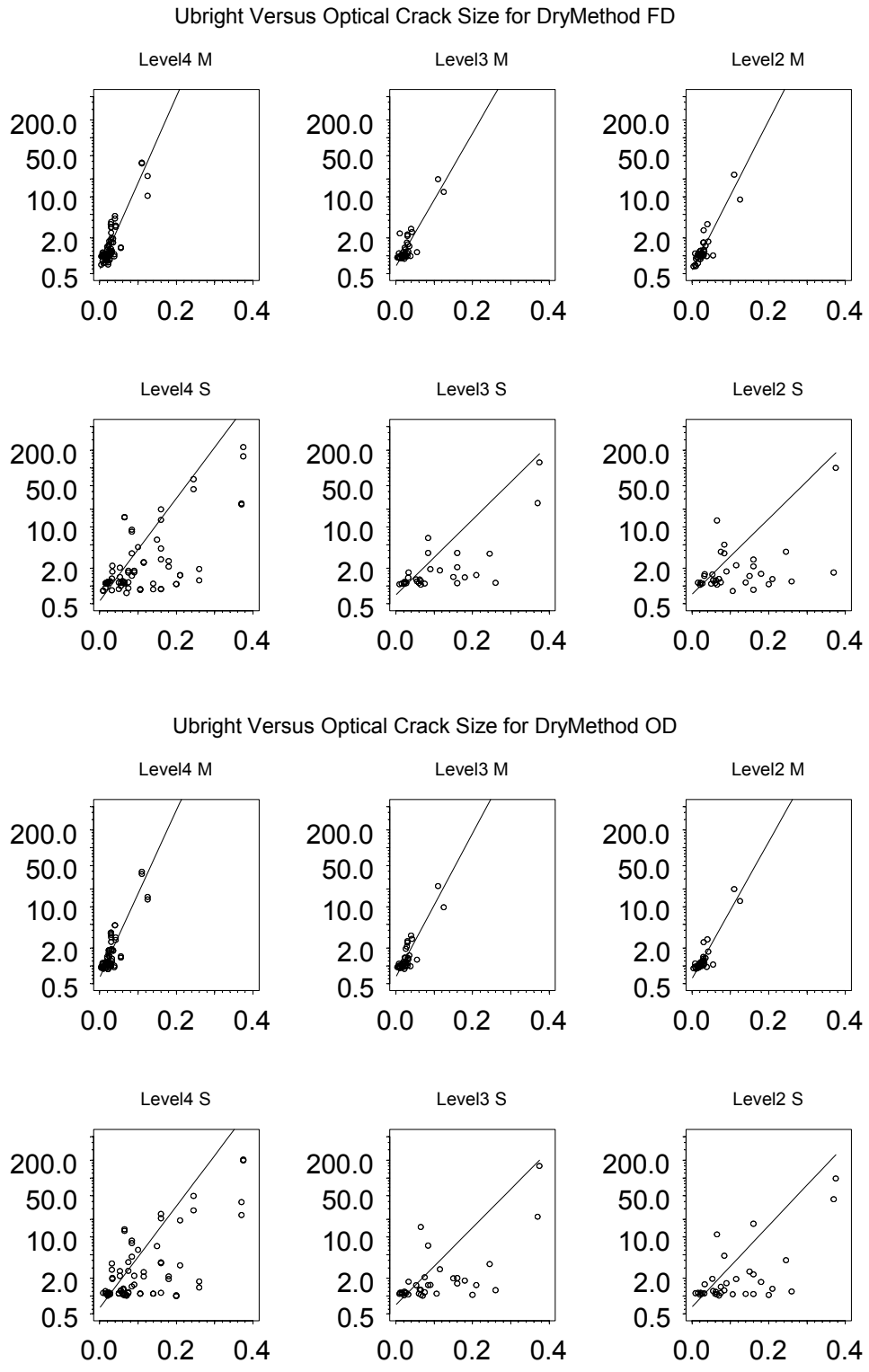
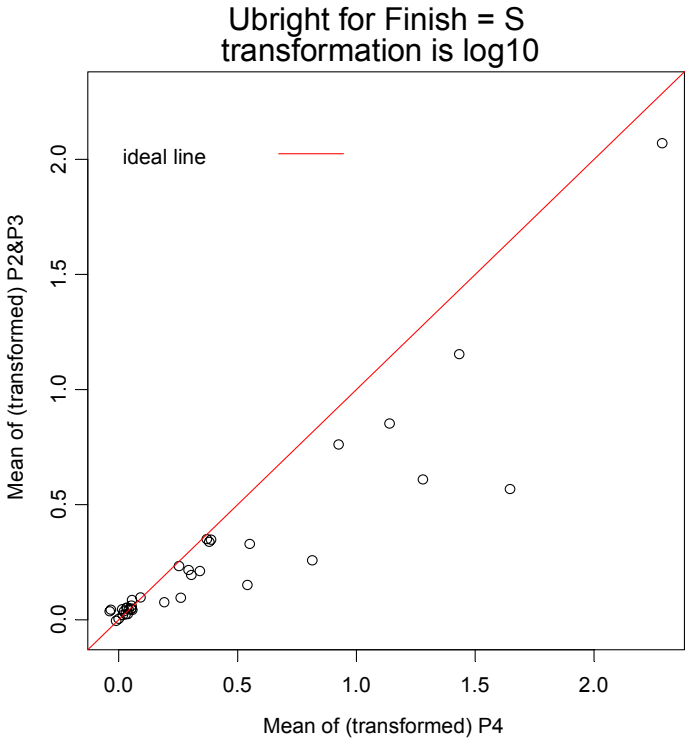


Figure 15. Regression analysis for flash dry (above) and oven dry (below).



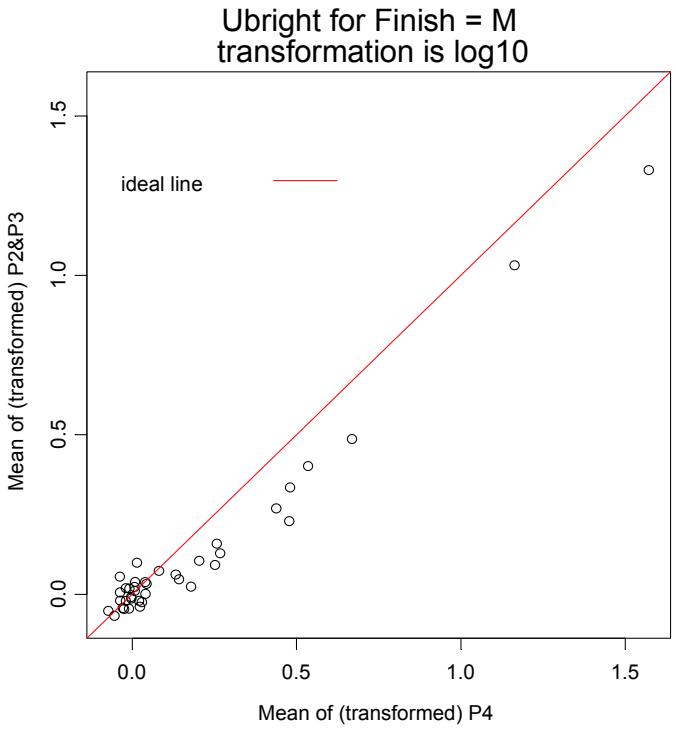


Figure 16. Transformation analysis used to compare level 4 to level 2/3.

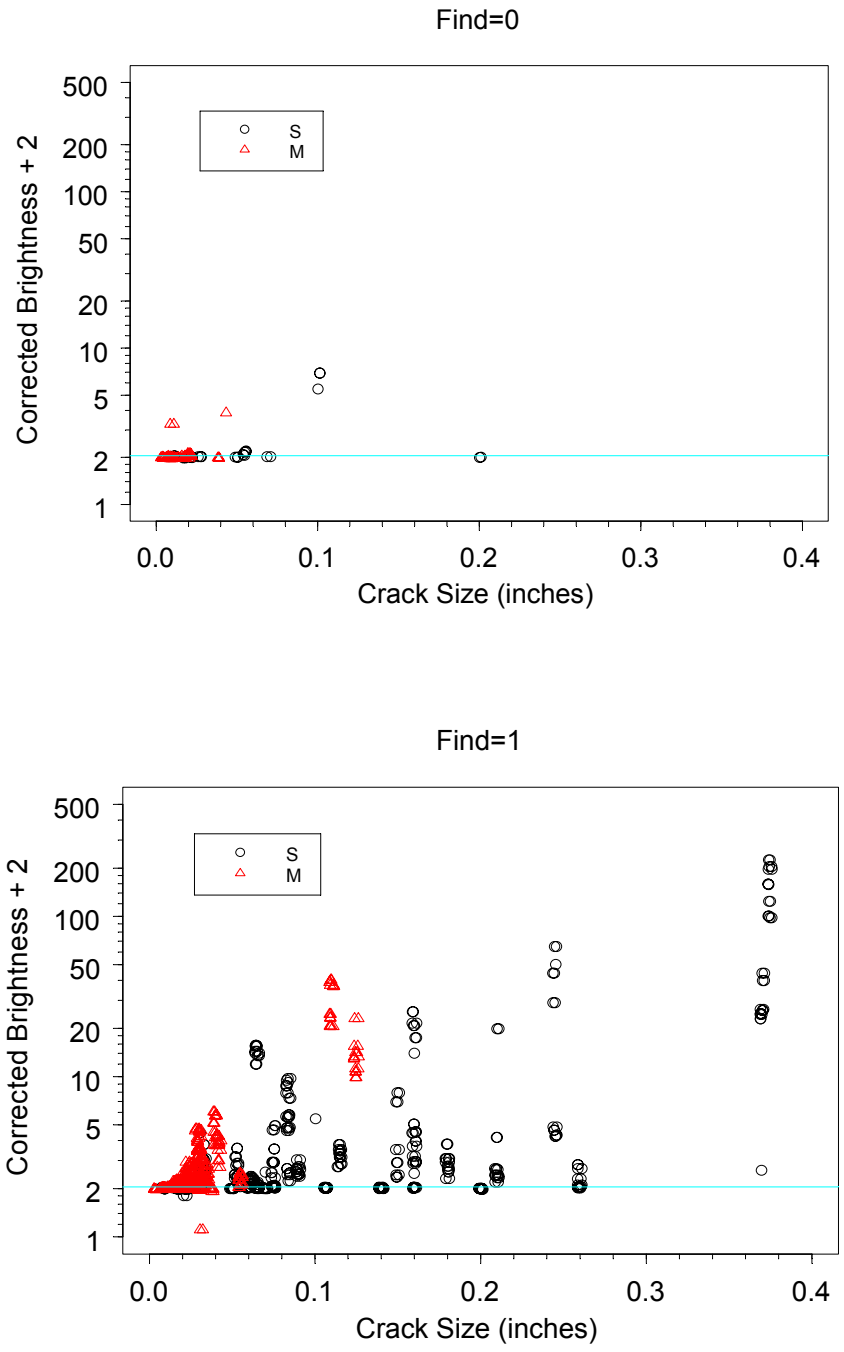


Figure 17. Misses (top) and finds (bottom) shown as function of brightness and crack size. An offset value of 2 was added to all points to shift the data away from the x axis.

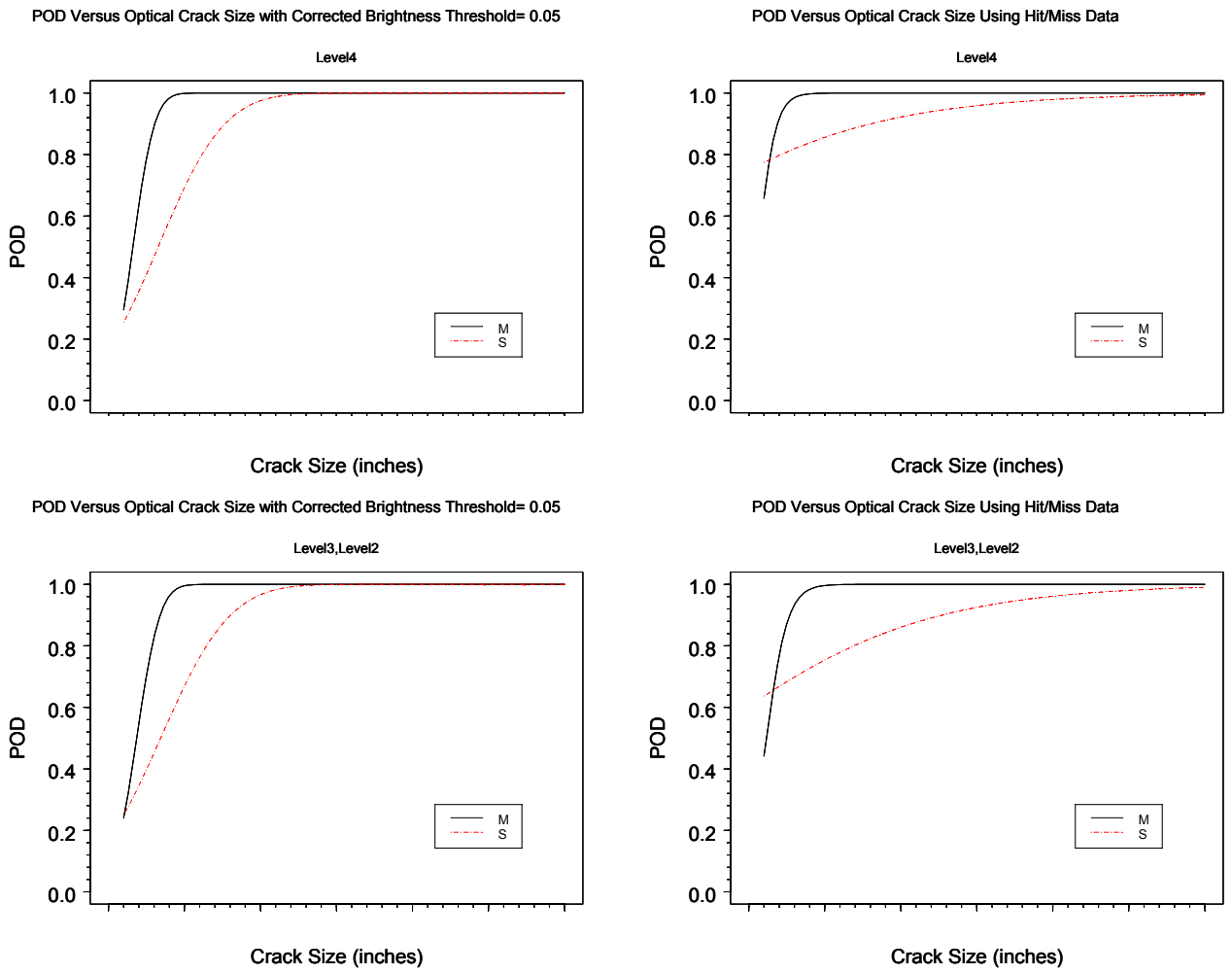


Figure 18. POD curves using threshold analysis (left) and hit/miss analysis (right).

POD analysis was also performed by Rummel for the two inspectors with details of the analysis provided in Appendix B. A table summarizing the POD results is provided in Table 4 and data is graphed in Figure 19. The crack lengths are reported as normalized values using the smallest crack length from the 90/95 point. This allows comparison of the each of the studies without reporting the actual crack lengths. Because all cracks were in the same location on the sample, it was felt that reporting the 90/95 crack lengths was inappropriate. Note that differences were found between the penetrant types but significant differences were not found for the drying method. Level 2 showed a smaller 90/95 crack size than level 3 for the parameters used in this study as reported for Inspector A. In future POD studies, more specific guidance on accept/reject criteria is recommended which should reduce the variability in false calls.

Table 4. Comparison of normalized crack sizes for each of the penetrant studies. Note that three inspectors participated in the study. Inspector A was familiar with the samples while inspectors B and C were seeing the samples for the first time during the week of the study. This contributes to the false call rates of Inspector B and C.

Run no. (Inspectors)	Description	Normalized 90/95 crack length*		False calls	
		Inspector A	Inspector B/C	Inspector A	Inspector B/C
3 (A/B)	Level 4, 185 FD	1.00	2.61	6	18
4 (A/B)	Level 4, 250 OD	1.27		6	21
5 (A/B)	Level 4, 225 OD	1.16	0.64	7	18
6 (A/B)	Level 4, 185 FD	1.07	0.66	5	20
7 (A/B)	Level 3, 185 FD	1.91	1.07	5	23
8 (A/B)	Level 3, 225 OD	2.32	0.75	6	18
9 (A/B)	Level 4, 225 OD	1.09	0.64	5	33
10 (A/C)	Level 2, 225 OD	1.61	1.23	7	10
11 (A/C)	Level 2, 185 FD	1.57	2.5	7	4

*Crack sizes were normalized using the smallest 90/95 crack length for inspector A.

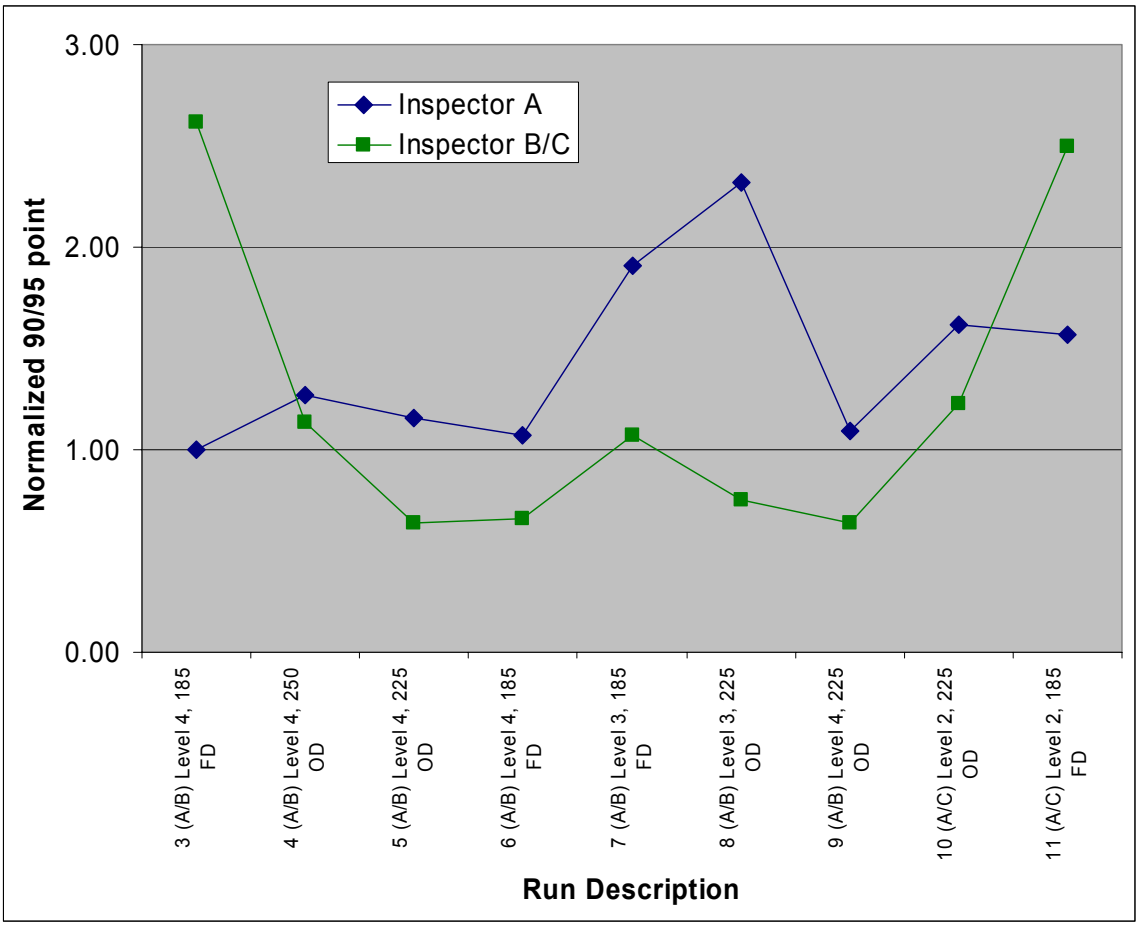


Figure 19. Data for normalized 90/95 point for two inspectors as a function of penetrant type and drying method.

A summary of samples which did not have a measureable brightness are shown in Table 5 for each of the runs. The sample designations are listed along with crack size and surface finish. The shaded areas indicate those runs for which brightness was not measurable. Note that more cracks were not measurable for levels 2 and 3 than level 4 penetrant.

Table 6. Tabulation of samples for which a brightness measurement could not be made.

Sample Description			Run 2 – Level 4 – 225 OD	Run 3 – Level 4 – 185 FD	Run 4 – Level 4 – 250 OD	Run 5 – Level 4 – 225 OD	Run 6 – Level 4 – 185 FD	Run 7 – Level 3 – 185 FD	Run 8 – Level 3 – 225 OD	Run 9 – Level 4 – 225 OD	Run 10 – Level 2 – 185 FD	Run 11 – Level 2 – 225 OD
ID	Crack size (inches)	Surface finish*										
A6	0.017	M		X		X	X	X		X	X	X
A13	0.009	S				X					X	
A15	0.075	S						X				
A22	0.160	S							X			
A23	0.100	S		X	X	X	X	X	X	X	X	X
A24	0.070	S					X	X				
A17A	0.106	S						X				
A20A	0.007	M	X								X	X
A31A	0.017	S						X			X	X
A37A	0.011	S	X	X	X	X	X	X		X	X	X
B8	0.022	M										X
B15	0.010	M										X
B20	0.200	S						X				
B4B	0.015	M		X								
C25C	0.140	S						X	X			
C28C	0.05	S						X	X			X
TOTAL			2	4	2	4	4	10	4	3	6	8

*M – machined surface. S – shot peened surface.

Conclusions

Statistical analysis led to the following conclusions:

For the sample size and crack size, differences were not found between the two drying methods. Factors not considered include thermal mass and crack volume which will be accessed as part of future studies using real parts and appropriate fixtures.

Differences were found between the two surface finish conditions. Detectability in shot peened surfaces present on these samples was lower than machined surfaces.

Differences were found between penetrant method with Level 4 found to be more sensitive than Levels 3 or 2. Differences between levels 2 and 3 were not significant for the rinse times used.

Supporting Documents

Relevant Industry Standards/procedures:

AMS 2647B - Fluorescent Penetrant Inspection Aircraft and Engine Component Maintenance

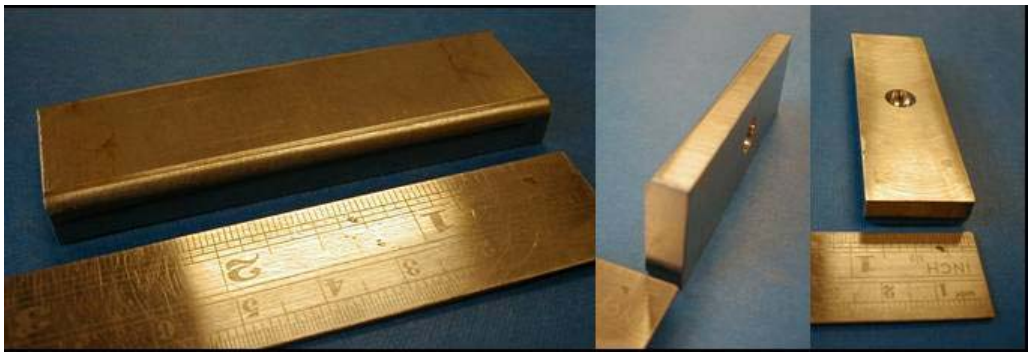
Publications/References:

"Engineering Studies of Cleaning and Drying Processes in Preparation for Fluorescent Penetrant Inspection (FPI)," FAA Report to be published in Spring 2003.

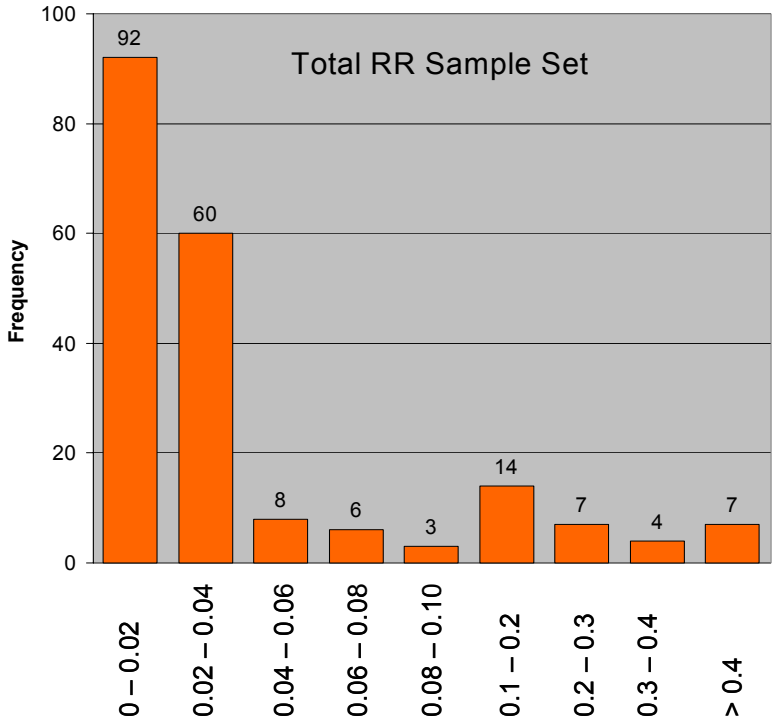
L. Brasche, B.F. Larson and R. Lopez, "A Review of Recent Research Studies of Cleaning and Drying in Preparation for Fluorescent Penetrant Inspection – Parts I and II" to be published in Review of Progress in QNDE, Vol. 22, edited by D. O. Thompson and D. E. Chimenti, 2003.

Appendix A – Sample Selection

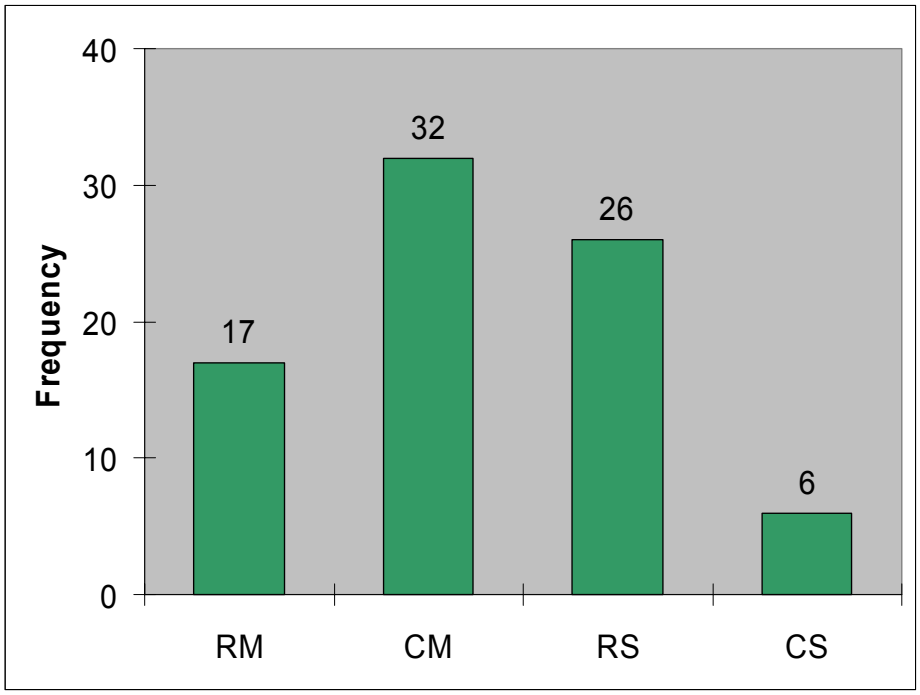
Rolls Royce has generated over 200 cracks in forged Ni bars such as the one shown here. The cracks were generated in three point bending without the use of starter notches.



Cracks sizes range from 8 mils to 375 mils with the majority of cracks from 10 to 100 mils. Figure 1 provides a histogram of crack sizes. Note that bin widths are 0.02 for the first five bins and 0.1 for the last four.



Selection of the final crack distribution included consideration of several factors. Samples were generated with two surface finishes, M – machined, and S – shot peened, and from two disk locations, C – circumferential, and R – radial. An effort was made to have a similar number of samples from each of the types and over the range of crack sizes. The ability to do so was constrained by the overall number of samples for a given type. Taking this and other factors into account, the final distribution of each of the types for the 81 cracks selected is shown below:

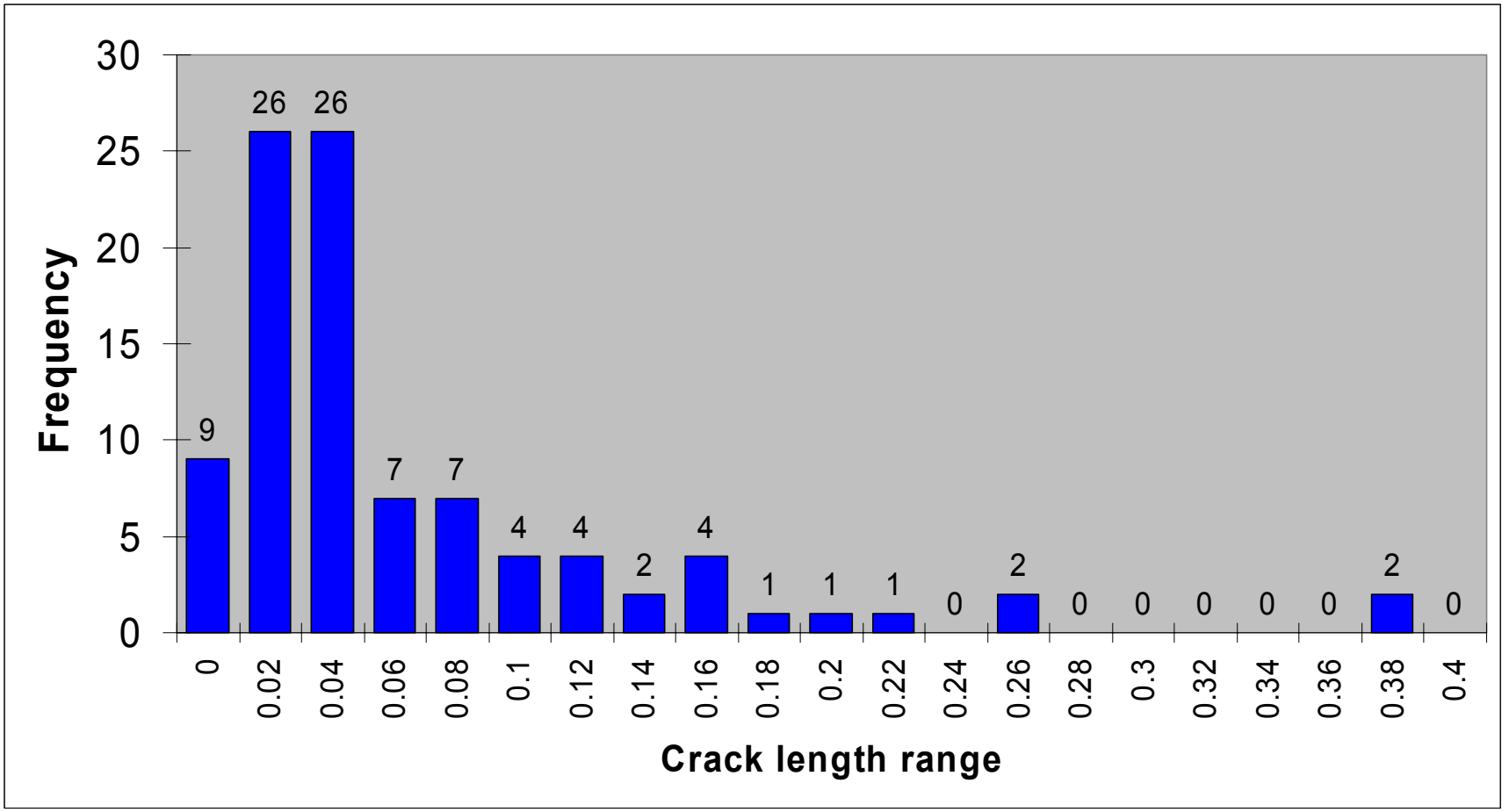


Another factor is selection of the final sample set was number of cracks per panel. . A preference was given to samples with single cracks. However we were unable to arrive at a full sample set with out using some multiple crack samples. Of the 81 crack samples selected, 58 had single cracks, 11 had two cracks and 3 had three cracks and nine contained no cracks.

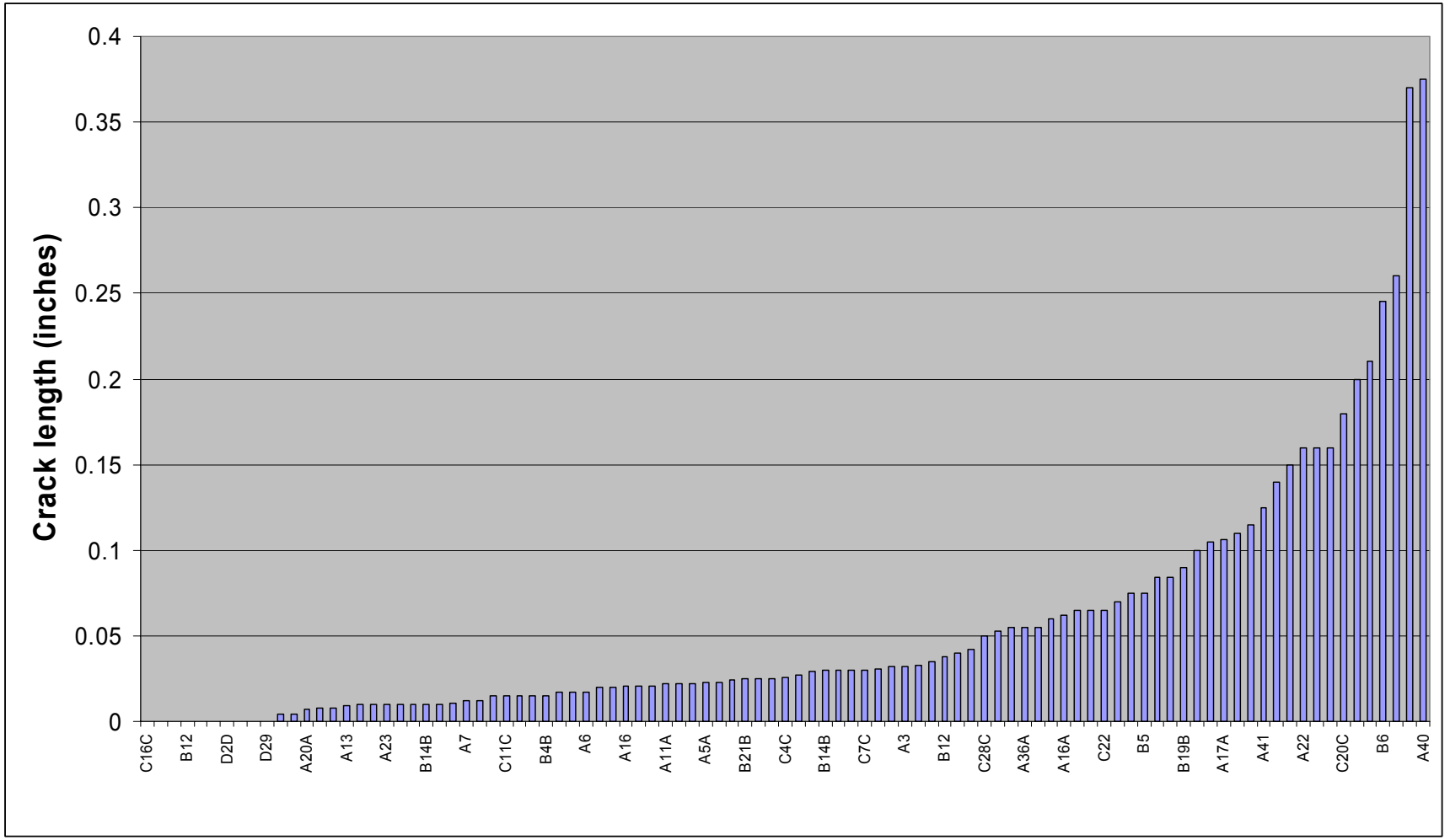
The crack size distribution was also considered in final sample selection. An effort was made to balance the number of small and large cracks while also taking into account the surface finish/disk location factors discussed above. A list of the final cracks selected for the study is provided followed by a histogram showing the cracks per 20 mil size range and the overall crack distribution as a function of crack length. In the table that follows the color codes are used to indicate the surface finish and disk locations. Sample ID's that are shaded dark green indicate samples with multiple cracks.

Batch 1					Batch 2					Batch 3				
Cracks per specimen	Disk location	Surface Finish	Specimen ID	Crack Size (in)	Cracks per specimen	Disk location	Surface Finish	Specimen ID	Crack Size (in)	Cracks per specimen	Disk location	Surface Finish	Specimen ID	Crack Size (in)
1	**C**	**M**	A1A	0.008	1	C	S	A40	0.375	**1**	C	S	**A15A**	0.37
1	**R**	**S**	**A10**	0.032	**1**	**C**	**M**	**A41**	**0.125**	**1**	**R**	**S**	**A30A**	0.015
1	R	M	A11A	0.042	1	C	M	A5A	0.023	**1**	**R**	**S**	**B3**	**0.084**
2	R	M	A11A	0.022	1	C	M	A6	0.017	1	R	S	B30B	0.26
1	R	M	A12A	0.02	**1**	**C**	**M**	**A6A**	**0.008**	**1**	**R**	**M**	**B31B**	**0.025**
1	R	S	A13	0.009	1	C	M	A7	0.055	**1**	**R**	**M**	**B32B**	**0.031**
1	**C**	**M**	**A14A**	**0.015**	2	C	M	A7	0.012	1	R	M	B36B	0.025
1	**R**	**S**	**A15**	**0.075**	1	C	M	A8A	0.02	**1**	**R**	**M**	**B37**	**0.03**
1	C	S	A16	0.084	1	R	M	A20A	0.007	1	C	M	B4B	0.015
2	C	S	A16	0.021	1	R	S	A23	0.01	**1**	**R**	**S**	**B5**	**0.075**
1	**C**	**S**	**A16A**	**0.062**	1	R	S	B1	0.023	1	**R**	M	**B8**	0.022
1	**C**	**S**	**A17A**	**0.106**	1	R	M	B12	0.038	1	**R**	M	B8B	0.024
1	C	M	A18A	0.04	2	R	M	B12	0.012	1	**R**	M	B22	0.01
2	C	M	A18A	0.004	3	R	M	B12	0	1	R	S	C20C	0.18
1	R	M	A19	0.029	1	R	M	B12B	0.035	2	R	S	C20C	0.105
2	R	M	A19	0.017	2	R	M	B12B	0.01	**1**	**R**	**S**	**C22**	**0.065**
1	R	M	A21	0.11	1	R	M	B14B	0.03	1	R	S	C25C	0.14
2	R	M	A21	0.055	2	R	M	B14B	0.01	1	R	S	C26C	0.15
3	R	M	A21	0.01	3	R	M	B14B	0.01	2	R	S	C26C	0.1
1	**R**	**S**	**A22**	**0.16**	1	R	S	B19	0.06	1	R	S	C27C	0.027
1	**R**	**S**	**A24**	**0.07**	2	R	S	B19B	0.09	**1**	**R**	**S**	**C28**	**0.033**
1	**C**	**M**	**A3**	**0.032**	1	R	S	B19B		**1**	**R**	**S**	**C28C**	**0.05**
1	R	S	A31A	0.017	**1**	**R**	**S**	**B1B**	**0.053**	1	C	S	C35C	0.16
1	R	M	A32A	0.004	1	R	S	B2	0.022	1	C	S	C36C	0.16
1	R	S	A36A	0.055	1	R	S	B20	0.2	1	R	M	C4C	0.026
2	R	S	A36A	0.065	**1**	**R**	**S**	**B20B**	**0.115**	2	R	M	C4C	0.021
1	R	S	A37A	0.011	1	R	M	B21B	0.025	1	R	M	C7C	0.03
1	R	S	A38A	0.065	1	R	M	B27B	0.015	0	C	M	C13C	
1	R	M	B15	0.01	**1**	**R**	**M**	**B28B**	**0.03**	0	C	M	C38C	
1	R	S	B35B	0.21	1	R	S	B29	0.021	0	R	M	D29	
1	C	M	C11C	0.015	1	R	S	B6	0.245					
0	C	M	C16C	0	0	C	M	A3A						
0	R	M	D20	0	0	R	M	D33						
0	R	M	D27	0	0	C	M	D2D						

List of samples used in the study separated into the three batches. Crack lengths are also listed.



The graph above provides a histogram of the samples as categorized by crack lengths.



The graph above shows the crack length distribution for the samples selected for the drying study. Sample IDs are listed for some samples along the x axis.

Appendix B – Summary of POD calculations – hit/miss analysis

Introduction:

The reliability of a precision fluorescent penetrant inspection system is dependent on:

- Capability – As measured by probability of detection (POD) assessments
- Reproducibility – Derived from control of system calibration (for fluorescent penetrant operations, this element reflects control of operating equipment, processing materials and part preparation)
- Repeatability – Derived from process control and variances introduced by process parameter control and human factors variables

Inspection Capability and Probability of Detection (POD):

The end-to-end capability of an inspection procedure is ascertained by the probability of detection (POD) method. POD provides a snapshot in time for the detection capability of a system on the test object (material / defect / crack) type. The POD assessment accounts for specific response to an applicable test object and artifacts (cracks) and takes into account for crack-to-crack variance. It is thus a useful tool for validation of an inspection procedure and as a periodic method of revalidating a system / inspection process. Once established, the method is useful for assessing the effects of inspection parameter variances on overall response. In this mode, it is essential to assess one inspection parameter at a time while holding all other parameters constant.

For fluorescent penetrant inspection, human factors variations may constitute a significant contribution to process repeatability and this variance may be reduced by assessment of process parameters using the same processing operator and the same inspector. The end-to end (POD) result is a comparative analysis and may provide a measure of the effect of variance of a specific processing parameter.

For purposes of economy in analysis of POD results, a causal response relationship for (hit/miss) inspection data is generated using a maximum likelihood method and data are then fit to a log logistics (POD) model to provide the POD response. A basic requirement of the maximum likelihood analysis is a distribution of responses that include normal distributions of “missed” detection opportunities and “hit” detection opportunities (usually distributed as a function of crack size / length or depth). For non normal distributions and/or distributions with few misses, the maximum likelihood analysis will fail to converge and will fail to produce a result that is compatible with the POD model. In those cases, an estimate of the causal response model may be provided by using the larger cracks in the data set to provide a basis for a causal response model (slope and intercept) and a basis for input to the POD model. **The estimated response is not rigorous and should be used only as a basis for comparison and for adjustment of the distribution of the test set. Data sets that do not converge are so identified and results should be used accordingly.**

Causal model results are fit to the log logistics (POD) model to generate the detection capability as a function of crack size. The log logistics model reflects the merging of Gaussian distributions of signal and noise responses that are characteristic of nondestructive inspections.

The POD analysis method does not account for false calls (false identification of a crack when no crack is present). A false call indicates a lack of finite discrimination for the inspection sequence and may be a basis for rejection of an inspection sequence or

operator. In production, a false-call is primarily of economic concern and may not be significant if a more sensitive discrimination method can be readily applied to confirm the presence of a crack. **(NOTE: Visual inspection under white light does not qualify as a more sensitive discrimination process.)** For POD assessments, false calls should be resolved as a method of process control of the test specimens involved. One method of assessment is by repeating inspection sequences using different inspectors.

The POD assessment method does not account for a level of expectation for finding a crack and test specimens that contain cracks at a fixed location (sometimes termed "focused inspections") necessarily bias results unless a large number of blank specimens are included in the assessment. The expectation factor is economic in both the availability of specimens and the availability of blank specimens. It may be reduced by selecting a specimen grid, by instructions to inspectors to provide a systematic inspection of multiple grid locations, and by using the same inspectors for comparative analyses for inspections involving variation of a single processing parameter.

The POD method as applied to drying assessments:

Few experimental assessments are ideal for the purpose intended. Economics and practical considerations must be included in design of experiment and in analyses of results. The test specimens used in the current drying assessments are characterized by the following:

1. Both shot peened and as-machined specimens containing small fatigue cracks were combined in the inspection sets. Crack closure and morphology differ for these two conditions and may have accounted for some of the variance in data convergence. In addition, the peened specimens provide a different background for the fluorescent penetrant process. A high background is a source of false-calls.
2. Cracks were located at the same location in all specimens and thus provided a high level of expectation for all inspectors. Few unflawed specimens were available.
3. The crack size distribution was limited and was reflected in difficulties in convergence of the data.
4. All cracks were small and thus the large reservoir (water retention) volume for large cracks was not assessed.

The purpose and results of the assessment are valid within the parameters and variances identified. Effects of small sample size and expectations were reduced by use of two inspectors for all assessment sequences. Those POD analyses that did not converge are not rigorous but provide a basis for comparison on assessment sequences. Effects for large cracks were not assessed in these sequences and such results may not be consistent with the findings in these assessments.